TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Mechatronics, Informatics
and Interdisciplinary Studies

Design of DC Fast Charging Station for Light Electric Vehicles

Master Thesis

Study programme: N0714A150003 Mechatronics
Author: **Iana Chertkova**
Thesis Supervisors: Ing. Pavel Jandura, Ph.D.
Institute of Mechatronics and Computer Engineering

Thesis Consultant: Václav Klouda
Siemens s.r.o.

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Master Thesis Assignment Form

Design of DC Fast Charging Station for Light Electric Vehicles

Name and surname:	**Iana Chertkova**
Identification number:	M21000201
Study programme:	N0714A150003 Mechatronics
Assigning department:	Institute of Mechatronics and Computer Engineering
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Rules for Elaboration:

1. Do a research on the issue of charging stations for light electric vehicles focusing on DC fast charging (DCFC).
2. DCFC will be based on UR120100 power modules controlled by CAN or RS485 communication bus.
3. Design a proprietary CAN based DC charging communication protocol between the station and experimental vehicle. Protocol for DC charging must be compatible with AC charging system as both systems will share communication line in the CCS vehicle inlet.
4. Design and implement a control system with HMI for DCFC.
5. Design and implement a client for remote monitoring and control of DCFC using one of the standardized protocols.

Scope of Graphic Work: –
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Thesis Form: printed/electronic
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List of Specialised Literature:

[1] EICKELMANN, Jens, 2017. *Driving Force Electromobility: Busness development and rowth strategies in the field of electromobility*. Germany: Phoenix Contact E-mobility.
[2] CHARGEPOINT, INC., 2016. *Electric vehicle Charging: Basis and Beyond*. Campbell, CA.
[3] *Design Guide for Combined Charging System*, 2015. V4-2. Berlín: Open Charge Alliance.
[4] VENKATA PRUTHVI, Thota, Niladri DUTTA, Phaneendra Babu BOBBA, B Sai VASUDEVA, S.K. TUMMALA a P.B. BOBBA, 2019. Implementation of OCPP Protocol for Electric Vehicle Applications. *E3S Web of Conferences* [online]. **87** [cit. 2019-10-06]. ISSN 2267-1242. Dostupné z: doi:10.1051/e3sconf/20198701008
[5] ALCARAZ, Cristina & LOPEZ, Javier & WOLTHUSEN, Stephen. (2017). OCPP Protocol: Security Threats and Challenges. IEEE Transactions on Smart Grid. PP. 1-1. 10.1109/TSG.2017.2669647.

Thesis Supervisors: Ing. Pavel Jandura, Ph.D.
Institute of Mechatronics and Computer Engineering

Thesis Consultant: Václav Klouda
Siemens s.r.o.

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L.S.

prof. Ing. Zdeněk Plíva, Ph.D.
Dean

doc. Ing. Josef Černohorský, Ph.D.
head of institute

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Design of DC Fast Charging Station for Light Electric Vehicles

Abstract

The thesis is devoted to the design of a direct current fast charging station for light electric vehicles. The work consists of two parts. The first part is a theoretical study of existing technologies in the field of charging stations. The second part is the design of the charging station itself, which consists of the hardware and the software part. The hardware part of the project describes all the components of the device and the scheme of their connection. The software part presents a proprietary protocol for interaction between the charging station and an electric vehicle, an algorithm for controlling the station with a human-machine interface, and a variant of organizing remote control and monitoring of the station.

Keywords: E-mobility, light electric vehicles, fast charging, DC charging, combined charging system, OCPP

Contents

List of abbreviations

AC – Alternating Current
CAN – Controller Area Network
CCS – Combined Charging System, charging standard
CHAdeMO - Charge de Move, charging standard
CP – Control Pilot
DC – Direct Current
EV – Electric Vehicle
EVSE – Electric Vehicle Supply Equipment
GB/T – Guobiao Standards, charging standard
HMI – Human Machine Interface
HTTPS – Hypertext Transfer Protocol Secure
ID – Identification Data
JSON – JavaScript Object Notation, data format
LEV – Light Electric Vehicles
OCPP – Open Charge Point Protocol
OPC UA – Open Platform Communications United Architecture
OS – Operating System
OSI – Open Systems Interconnection
PE/PG – Protective Earth/Ground
PLC – Power Line Communication or
PLC – Programmable Logic Controller
PP – Proximity pin
PWM – Pulse-width modulation
RSA – Rivest–Shamir–Adleman, public-key cryptosystem
SAE – Society of Automotive Engineers, standards developing organizatio
SOAP – Simple Object Access Protocol
SSL – Secure Sockets Layer, protocol
SWCAN – Single-Wire CAN
TCP – Transmission Control Protocol
TLS – Transport Layer Security
URL – Uniform Resource Locator
V2G – Vehicle-to-grid
XML – Extensible Markup Language

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Introduction

Since its inception, the automotive industry has been one of the most important and rapidly developing industries. Nowadays, individual vehicles are present in the lives of most of the world's population. The rapid growth of urbanization creates a need for new models of urban mobility organization. Models that would solve the problems of current transport. The introduction the Light Electric Vehicles into the urban transport system reduces or even eliminates many of these problems. The term light electric vehicle or LEV covers a wide array of different vehicles ranging from e-scooters and e-bikes to e-forklifts, e-motorbikes and low-speed electric vehicles [1].

The dominant power source used in vehicles today is liquid fuels such as gasoline or diesel. The main problem with using such fuel is that tailpipe emissions negatively affect the ecology of the Earth. The emissions are a wide range of gases and particulate matter that cause global warming, acid rain, and harm to the environment and human health. The other important reason for using alternative energy sources for vehicles is reducing dependence on fossil fuels because it is limited and equal to dependence on fuel-producing countries. Light electric vehicles use electricity as a source of energy, which solves these problems.

Among other things, the growth of urbanization has led to huge traffic jams and a lack of parking spaces. Light electric vehicles reduce these problems since such vehicles take up significantly less space and are more manoeuvre.

Two main problems with LEV prevent their widespread adoption. The first problem is the almost complete lack of convenient charging infrastructure for this type of transport in cities. At the moment, LEV users can only charge their vehicles from a regular outlet at home or at work if possible. The second problem is the slow charging of electric vehicles relative to the refuelling speed of conventional gasoline or diesel vehicles. The way to solve these problems is to create a suitable charging infrastructure [1].

The following charging options for usual electric vehicles are mainly considered:

1) Battery swapping. It is a quick way of recharging, but this is not suitable for light electric vehicles as they all have different batteries [3, p. 78-80].

2) Wireless Power Transfer is a promising method of charging, but it is currently under development and has the problem of affecting the internal systems of vehicles that operate at the same frequency as charging [3, p. 74-78].

3) AC charging. The alternating current charging station is cheap but slow. The average charging time is about 2,5 hours for an electric vehicle with a range of around 100 km, which is not suitable for public charging stations [3, p. 68-71].

4) DC charging. This type of charging is much faster than AC charging, the average charging time is about 15 minutes for an electric vehicle with a range of around 100 km [3, p. 71-74].

Consequently, DC charging stations are currently the most convenient and well-developed option.

The purpose of this work is to design a DC Fast Charging Station for Light Electric Vehicles. All of the above is proof that this task is relevant and essential.

To implement the project, it is necessary to solve the following tasks:

1) Do research on the issue of charging stations for light electric vehicles focusing on DC fast charging

2) Design communication protocol between the station and experimental vehicle

3) Design a control system with HMI for DC fast charging

4) Design a client for remote monitoring and control of DC fast charging

1. Research on the issue of charging stations for light electric vehicles

The main difference between AC charging and DC charging is the location of the rectifier. AC charging uses the vehicle’s internal rectifier, while DC charging uses the rectifier inside the station. The speed of the charging process depends directly on the charging current, therefore the performance of the rectifier. The higher performance also means more weight and it is irrational to place such a rectifier inside a light electric vehicle.

The general view of the DC charger is shown in figure 1. The main structural elements of the charging station are the charging process controller, a power module which transforms AC from the electrical grid to DC and safety equipment such as residual-current devices, overvoltage protection devices etc. On the side of the light electric vehicle, there is also a charging process controller and the battery pack itself. These two systems communicate via a charging connector.

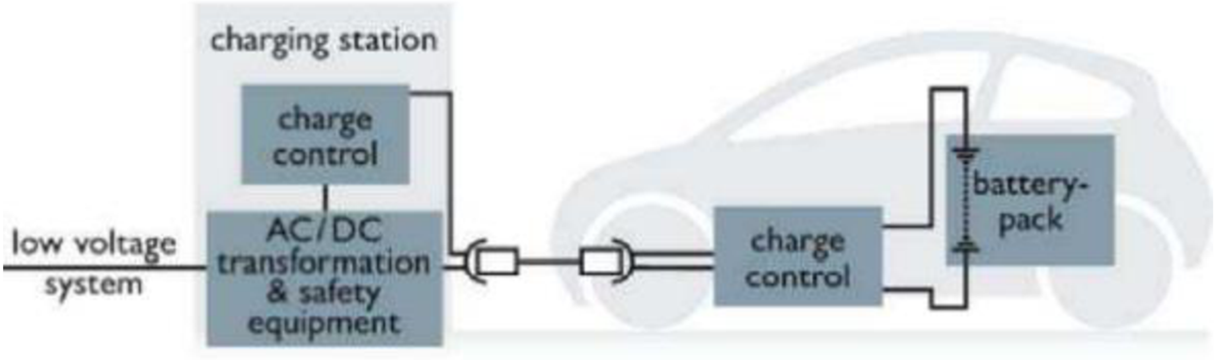


Figure 1. DC charging [3, p. 71-74].

High charging speed is achieved due to a large amount of charging current, which requires special control, both from the electric vehicle supply equipment and from the controller built into the vehicle.

Electric vehicles need to request the appropriate power in real-time, provide information about current statuses and errors, and provide internal protection for LEV elements. All this necessary information must be transmitted to the charging station through a connector. The electric vehicle supply equipment must process the information received from the electric vehicle and manage the charging module in accordance with the requested and currently available power.

The charging station must ensure the protection of the equipment and the user by safety standards. Also, It is required to have a convenient human-machine interface to control the charging process by the station users. Among other things, charging stations can be networked for more balanced control or be a stand-alone system.

All of the above describes charging stations in general, but in particular, they can differ in the connector standard, the method of charging, and the way for remote monitoring.

1.1. Overview of existing DC charging connector standards

At the moment, there are four main standards for DC fast charging connectors in the world, which are shown in Figure 2.

Figure 2. Connector types [4]

The standards include not only the structure of the connector but also the corresponding charging technology. American CCS type 1 and European CCS type 2 belong to the same connector standard which is called Combined Charging System. Therefore, the comparison considers combined charging system connectors in general. CHAdeMO and GB/T are also similar in approach but differ in implementation [5].

1.1.1. Combined Charging System connector

The combined charging system is an international charging connector standard created in Germany. This system is called combined because the connector is compatible with AC and DC charging.

Figure 3 shows the pinout of the combined type 1(CCS1) and type 2(CCS2) connectors. These connectors are based on type 1 SAE J1772 and type 2 «Mannekes» AC connector standards respectively. The main differences between the connectors are their shape and the number of AC phases. Type 2 connector has three phases, but type 1 has only one. Parts inherited from AC connectors are marked in blue color and the pins added for DC are marked in red. Combined charging systems inlet fully compatible with AC connectors on which they were based.

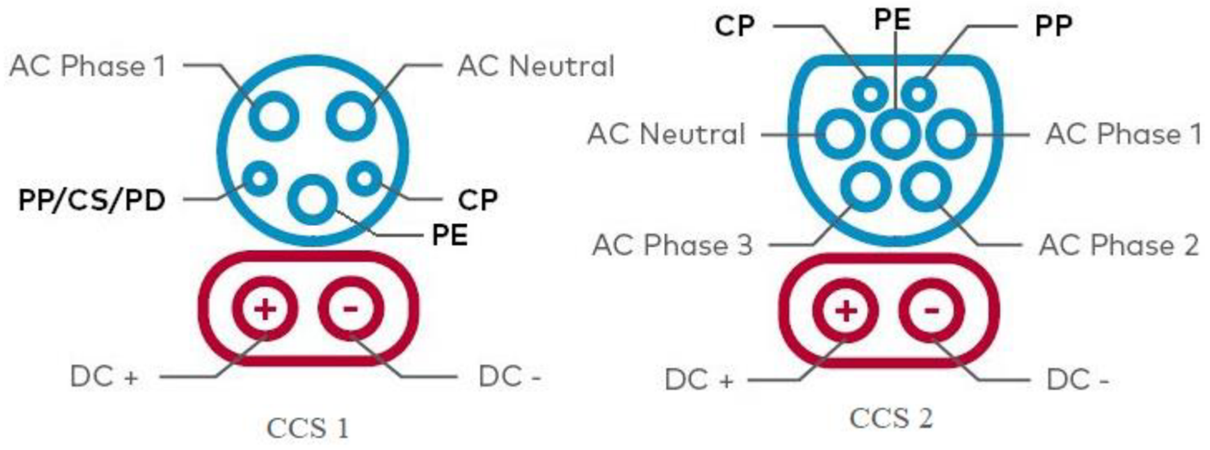


Figure 3. CCS1 and CCS2 pinouts [6]

A CP pin is used for controlling the charging process and the PP allows the electric vehicle to detect when it is plugged in or not.

At the beginning of the connection, the system operates in AC mode and is controlled via pulse-width modulation. A different duty cycle means a different state of charging. When the duty cycle is equal to 5 % the system changes the operating mode to DC mode. In this mode, the system is controlled via the Power Line Communication protocol. The communication is based on the OSI-Layer-Model containing 7 levels and each of the levels provides a dedicated task for the integrated communication process [7].

This model of work provides complex opportunities, such as a Vehicle-to-grid system or Plug & Charge. V2G is a system for powering the grid from electric vehicles. Plug & Charge is a feature that enables an electric vehicle to automatically identify and authorize itself. These features are useful for electric cars, but overkill for LEV.

As a result, this standard requires the implementation of overly complex protocols, the benefits of which are not justified for light electric vehicles. Also, such connectors are unsuccessful for small LEVs, as they are huge. It is inconvenient to use a 90x130 mm socket in a motorcycle or electric bike (Figure 4).

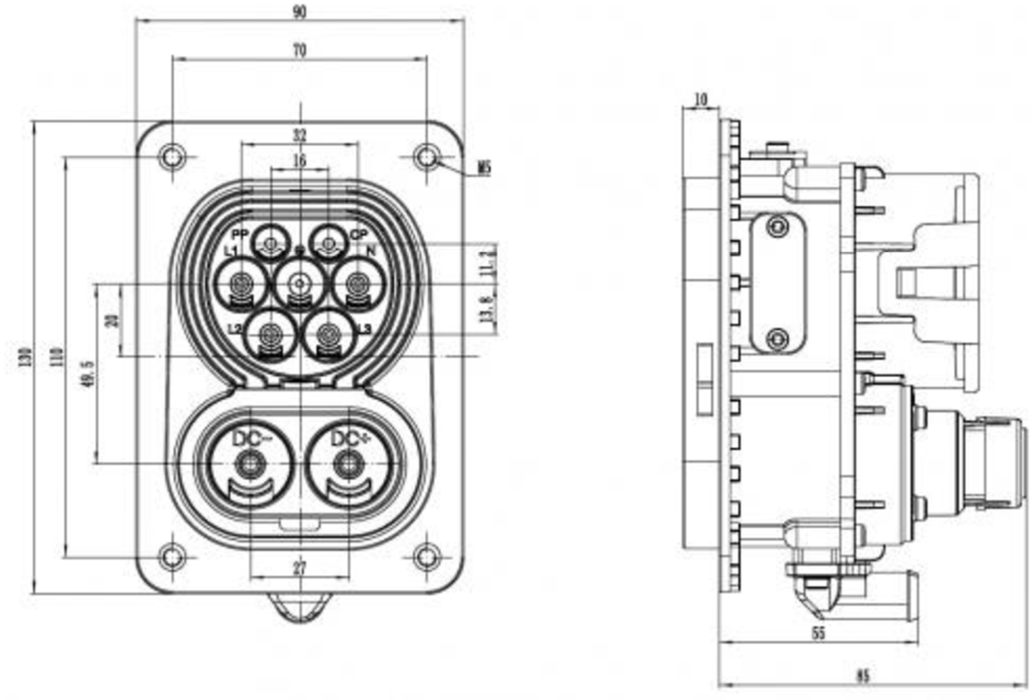


Figure 4. CCS2 socket size [8]

1.1.2. CHAdeMO

The CHAdeMO charging system is a national standard for EV charging in Japan. CHAdeMO can be used only for DC fast charging, so a separate AC inlet is required for AC charging.

Figure 5 shows the pinout of the connector. It consists of two DC power contacts, four control contacts for basic parameters such as enabling the charging process and proximity and two contacts for CAN bus communication.

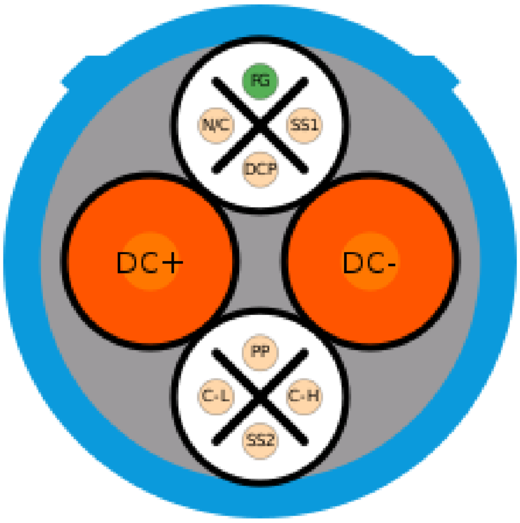


Figure 5. CHAdeMO pinouts [9]

The principle of operation is that the vehicle battery management system is connected to the fast charging station via the CAN bus and is formed as a master-slave system. The electric vehicle is the master whose messages have a lower ID than the charging station messages and, therefore, higher priority [10].

This model of work is much simpler than the combined systems model and it does not require the implementation of complex protocols.

The diameter of the CHAdeMO socket is about 77 mm (Figure 6), which is slightly smaller than the CCS. The CHAdeMO standard uses a hardware circuit to control whether a socket is connected and locked, unlike CCS which requires a separate message for checking.

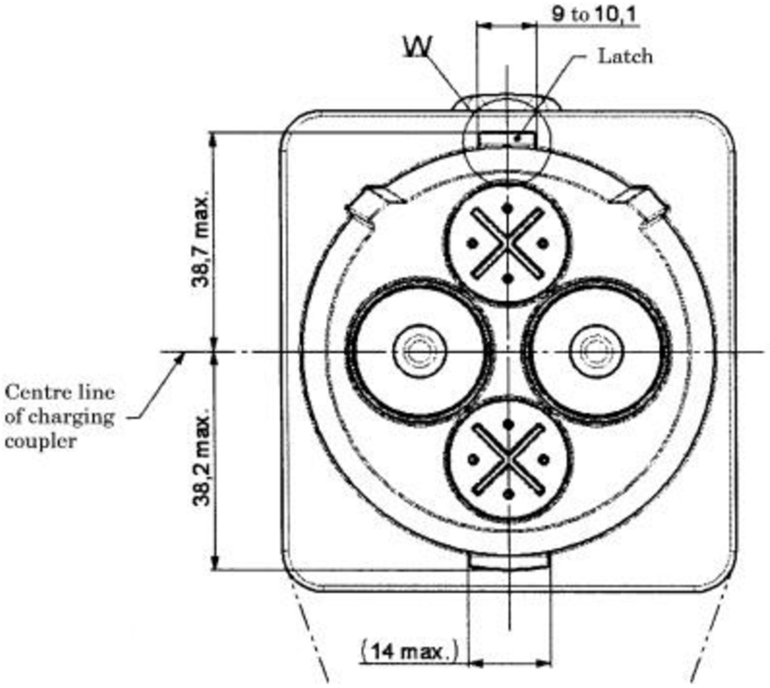


Figure 6. CHAdeMO size [11]

1.1.3. GB/T standard

GB/T is a Chinese charging standard that has two separate connectors for AC and DC charging. Only the variant for direct current will be considered here.

GB/T works almost the same as CHAdeMO and messaging also occurs over the CAN bus [12]. This is exactly the same interaction between the battery management system and the charging station in master-slave mode, but another form of message.

The size of the inlet is about 72 mm, which is slightly smaller than the size of CHAdeMO (Figure 7).

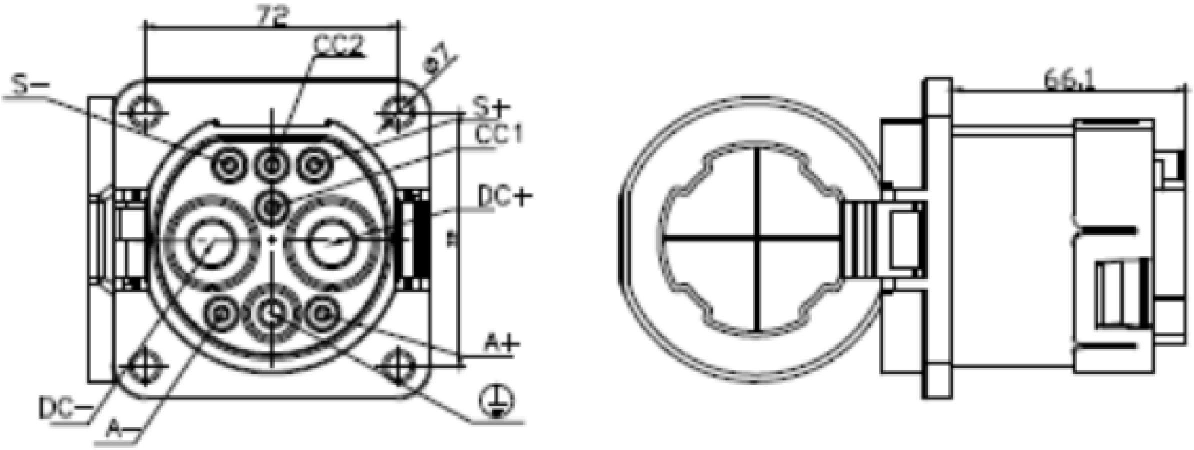


Figure 7. GB/T size [12]

Figure 8 shows the pinout of the GB/T connector, which shows that it is also similar to the CHAdeMO pinout, differing only in the presence of additional power pins (A + and A-).

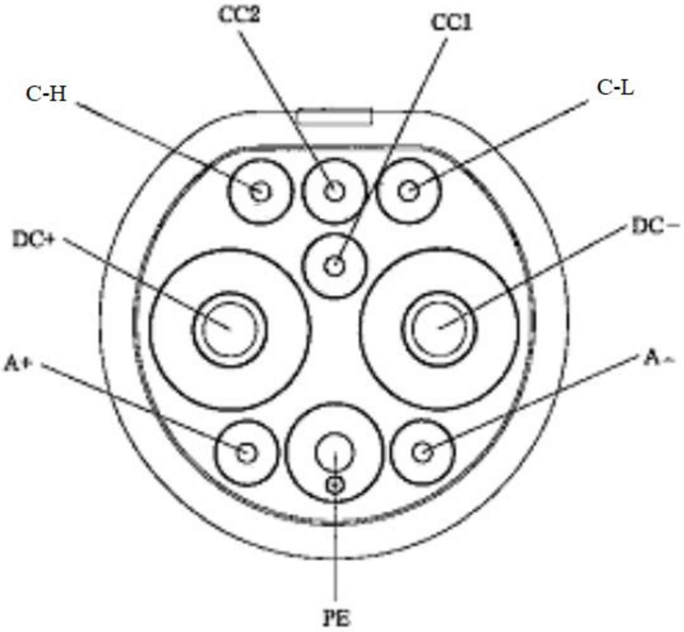


Figure 8. GB/T pinouts [13]

1.2. Monitoring and controlling organization

There are three different options for monitoring and controlling the system:

1) Non-networked system. The charging stations work as stand-alone units without network connectivity;

2) Networked system. Charging stations are controlled by the server called the charging station management system;

a) Closed Networks. Communication with the charging management system provides using proprietary protocols;

b) Open Networks. A publicly described communication standard between the charging stations and the charging station management system is used.

1.2.1. Non-networked system

This type of system allows using only the standard value of powers offered by the grid supplier. Non-networked charging stations may seem like an inexpensive option at first, but actually, they can cost more in the long run, as the inability to manage loads during peak hours increases energy costs. Also, there is no easy way to attract LEV drivers or let them know if the station is functioning or available, which increases downtime [14].

1.2.2. Networked system

Networked systems provide optimal control of charging stations. Figure 9 shows the structure of such a system. This type of control makes it possible to balance the load of the charging station to protect against failure and adjust prices depending on the current load of the station. The server can perform optimization based on the collected data using machine learning algorithms. Also, this format of the stations is convenient for the business owner, since, for example, it allows them to identify popular and unpopular points of the city and, accordingly, increase or decrease the number of stations.

Using mobile applications and real-time data, drivers can find available stations and charging rates before arrival. Users also can reserve a station before arrival. In the event of a failure, the charging station owner can instantly find out about it and fix the problem [14].

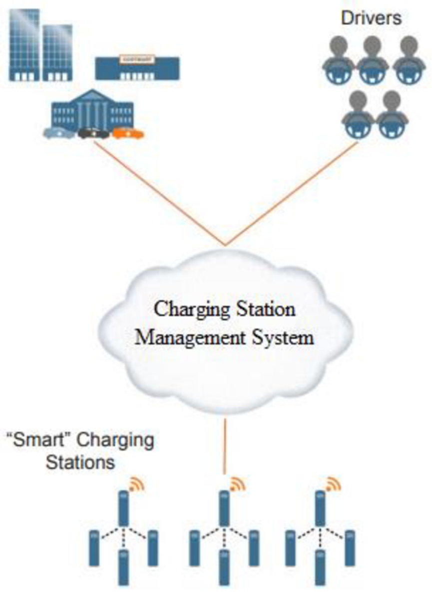


Figure 9. Structure of the networked system [14]

An open network system is better than a closed one because it gives charging station designers the option to choose better vendors for the charging station management system or change them at any time. It is also more convenient for users since the search for the nearest station can take place in one common application for all charging station providers.

2. DC Charging Station project

2.1. Components of the Charging Station

The system is built mainly on Siemens components, as it is reliable equipment with a high level of security. Such components are designed for difficult environmental conditions, including extended temperature ranges, and a large amount of electrical interference, and are also resistant to shock and vibration, which is extremely important for public charging stations.

The supply equipment is controlled by a Siemens S7-1511-1 PLC. ET 200SP 155-6 interface module is used to connect peripheral devices. The system uses two CAN buses, one for controlling the power module, and the other for communication with LEV. The UR120100-E rectifier is used as a power supply module. Siemens KT700 is used to display and control the charging process. The system also uses safety components, such as an isolation monitoring device and high-voltage relays with auxiliary contacts.

2.1.1. Control device

The control device is a PLC since it is a hard real-time system and it is suitable for difficult operating conditions. The Simatic S7-1500 controller series is the latest generation of Siemens controllers with an excellent set of functions and performance, therefore, a controller of this series with a 1511-1 PN processor was chosen to control the station (Figure 10). This is the simplest version of the S7-1500 controllers, but it is enough for the required task and it costs less than other controllers in this series. The convenient TIA Portal software is used to program this PLC. This controller works successfully at temperatures from -25 °C to 60 °C.

Figure 10. S7-1500 CPU 1511-1 PN [15]

2.1.2. HMI

To implement the user interface, a TFT display SIMATIC HMI KTP700 BASIC DP from Siemens was selected (Figure 11).

Figure 11. Siemens HMI [16]

This panel offers combined keyboard and touch control and has a high resolution and displays 64,000 colors. The characteristics are shown in table 1 [16].

Table 1. Panel characteristics

Screen diagonal	7 in
Display width	154.1 mm
Display height	85.9 mm
Resolution	800×480
Supply voltage	24 V
Protection class of the front part	IP65

2.1.3. Interface module

SIMATIC ET 200SP IM 155-6 PN ST is used as an interface module in the system (Figure 12).

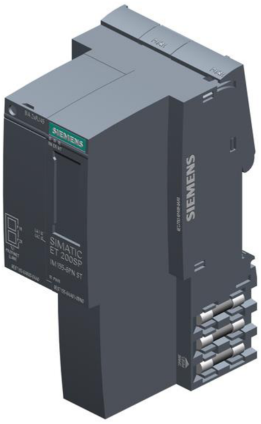


Figure 12. Interface module [17]

This module connects the ET 200SP distributed I/O system to the PROFINET IO. It supports up to 32 peripheral modules including a server module and mounted Bus Adapter BA 2×RJ45 [17].

2.1.4. CAN module

To interact with a light electric vehicle and a rectifier, two separate CAN buses are needed. Therefore, the system uses two ET 200SP CM CA CAN modules (Figure 13).

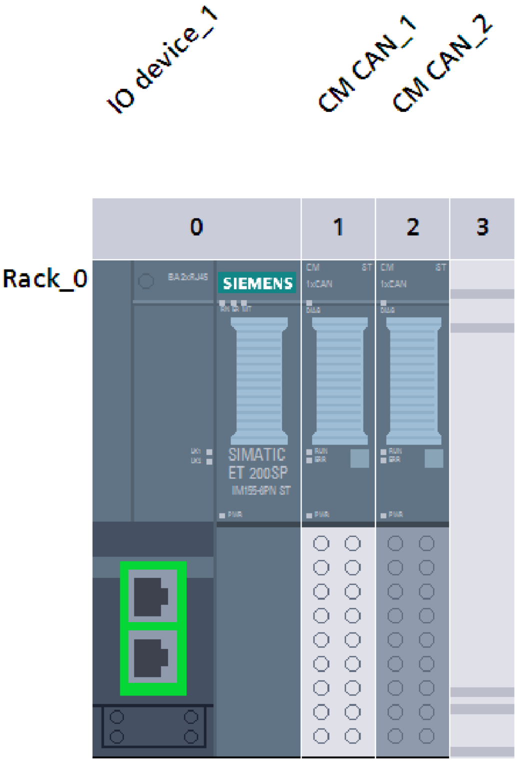


Figure 13. ET 200SP with CAN modules

These modules serve to connect to an ET 200SP system with the fieldbus CAN or CANopen and exchange data. ET 200SP CM CA CAN has a wide range of possible transmission rates from 10 kbit/s to 1000 kbit/s [18]. This is a useful property since SWCAN technology can be used for connection with LEV, which requires a speed of less than 33 kbit/s.

2.1.5. Power module

The highly efficient UR120100-E electric vehicle charging rectifier from UUGreen Power company was selected as the power module of the system. The control is carried out via the CAN bus, all inputs and outputs of the module are shown in Figure 14. The operating temperature of the module is in the range from -30 °C to +70 °C, which is good for an outdoor charging station. The size of the module is quite small and equal to 219.5mm (H)×84mm (W) ×395mm (D). The other advantages of this rectifier are high power factor correction, high efficiency, high power density, high reliability, and intelligent control.

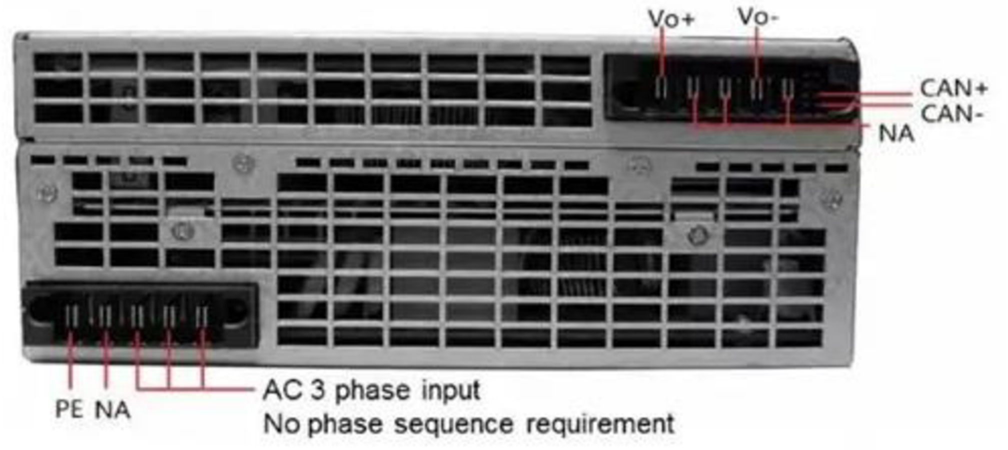


Figure 14. UR120100 rectifier

The power of the module is sufficient for fast charging of light electric vehicles and is equal to 15 kW. The output current range is from 0 to 100 A, and the output voltage is from 30 to 120 V, the characteristic is shown in Figure 15.

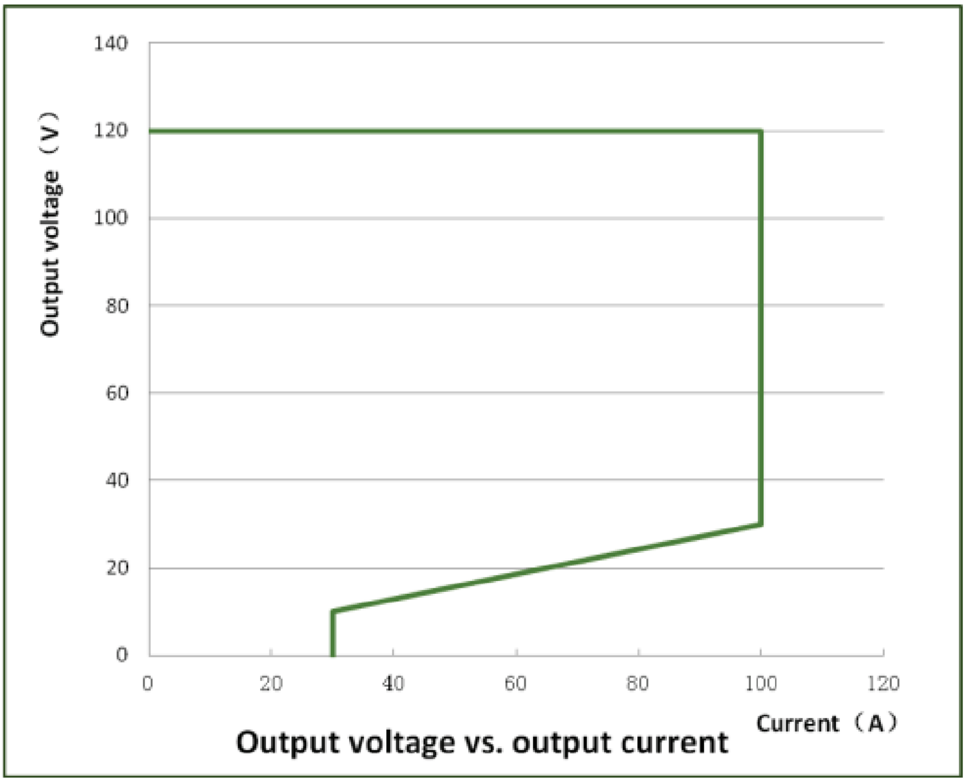


Figure 15. Volt-Ampere Characteristic [19]

2.1.6. Safety equipment

Firstly, to safely connect and disconnect the power supply, it is required to use two contactors for DC+ and DC-. For this purpose, KILOVAC EV200AAANA contactors from TE Connectivity have been selected. This is a budget, the lightest and smallest, sealed contactor in the industry. It has a built-in heat exchanger and is not subject to oxidation or contamination of contacts or coils, even during long downtime. Among other things, such contactors are more convenient than usual, since they have auxiliary contacts for monitoring the position of the power contact. A digital output module is required to close the contactors, and a digital input module is necessary to monitor the position of the power contact [20].

Secondly, to ensure the safety of the charging process, it is necessary to use an isolation monitoring device. The most popular isolation monitoring device is ISOMETER® isoEV425 with coupling device AGH420 (Figure 16). This device is designed specifically to ensure the safe operation of the charging station in accordance with the IEC 61851-23 “Electric vehicle conductive charging system - Part 23: DC electric vehicle charging station” standard [21]. This device measures voltage in the range from 0 to 1000 volts and insulation resistance. It can be controlled via Modbus RTU over RS-485, therefore it is necessary to include Siemens SIMATIC ET 200SP, CM PTP communication module for serial connection RS-485 module. The device can report overvoltage, undervoltage and insulation faults.

Figure 16. ISOMETER® isoEV425 with AGH420 [22]

2.1.7. Charging connector

It would be convenient for LEVs to have one common connector for DC and AC charging since it is problematic to place two separate sockets in a limited space. Therefore, it makes sense to develop a DC charging connector compatible with AC chargers. On the other hand, combo connectors for usual electric vehicles are also too big for light electric vehicles. In addition, the voltage of existing combined charging systems is unnecessarily high for LEVs. It starts at 200 volts, while a maximum of 120 volts is enough for such types of vehicles [23].

This problem can be solved using two different approaches. The first approach is to upgrade the existing AC type 2 connector so that it provides combined type charging. Such a system in AC mode will work similarly to the original type 2 connector according to the SAE J1772 standard [24] and for DC mode it is required to develop its protocol. This option is good because vehicles with an input of this type will be able to use the widely implemented standard for AC charging. The disadvantage of such a system is the natural limitations of the AC type 2 connector capabilities since it will not be able to conduct a current greater than 140 amperes.

The second approach is to design an appropriate connector that provides DC and AC charging according to its protocol of interaction with the LEV charging controller. The advantage of this approach is the ability to create maximum power charging without inherited limitations. The disadvantage, on the contrary, is the need to create a separate standard for AC charging and its implementation in the infrastructure.

Since the first approach contributes to the wider spread of LEV, it will be considered in this paper, but the developed protocol is theoretically possible to use in systems of the second type

2.1.8. Structure of the system

The final diagram of the device is shown in Figure 17. In addition to the components listed above, components are required to ensure compatibility of the connector with SAE J1772 and an external device for remote monitoring.

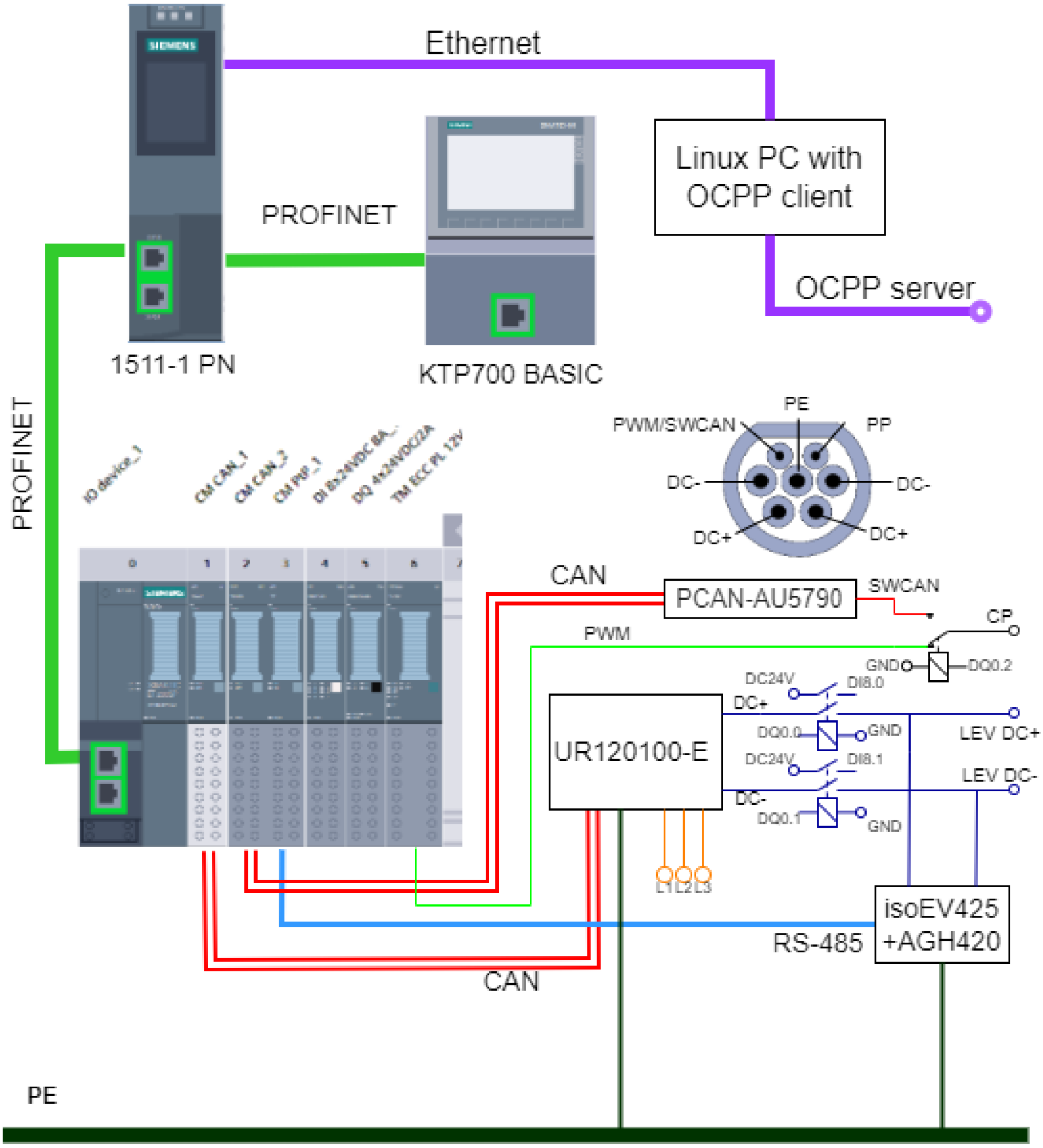


Figure 17. Structure of all system

For compatibility with SAE J1772, it is required to have a device that allows generating a 12V PWM signal, so the system uses SIMATIC ET 200SP TM ECC PL ST. This device was developed by Siemens for this very purpose. In the modified connector, it was decided to use only one wire for the CAN bus, so a device is required to convert a high-speed CAN into a single-wire CAN. For this reason, PCAN-AU5790 [25] device is used. Relay is required to switch between CAN and PWM modes. It is also controlled by the digital outputs of the controller, as well as contactors, but has no special requirements.

To provide remote monitoring, an external Linux PC is used, which interacts with the PLC via Ethernet and then connects to the central management system.

2.2. Communication between the station and vehicle

The existing standards for data exchange between electric vehicles and the charging station are based on the CAN bus or PLC protocol. Since the PLC approach is redundant for light electric vehicles and difficult to implement, it was decided to use the CAN bus.

2.2.1. The working principle of the connector

Due to the fact that LEV has a smaller battery capacity compared to conventional electric vehicles and they are charged at a lower voltage, it is possible not to use additional DC wires for combined operation mode. Therefore, it is possible to provide a combined mode of operation on a usual connector for AC charging. Figure 18 shows the operation scheme for DC and AC modes for the vehicle side. Such a scheme was proposed by Ing. Ondřej Mach from the Institute of Mechatronics and Computer Engineering of the Faculty of Mechatronics at the Technical University of Liberec.

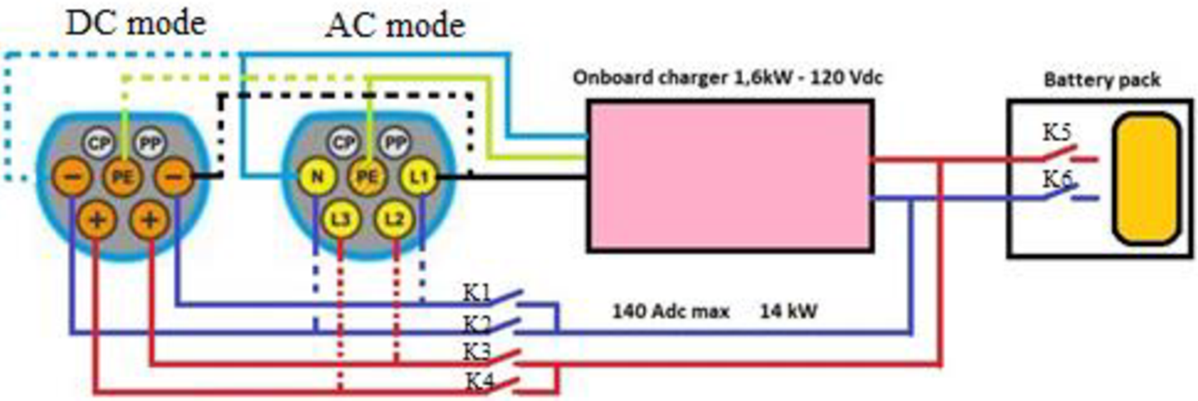


Figure 18. AC and DC modes scheme

In AC mode, pin L1 is a single phase of AC, and the N pin is neutral. These pins are connected to an onboard charger that converts AC to DC and supplies it directly to the battery pack of a light electric vehicle. Pins L2 and L3 are not used.

After closing K1-4, the DC mode is connected. In this mode, the pins of the phases L2 and L3 become DC+, and the L1 phase and N neutral become DC-. DC- is allowed not to be disconnected from the onboard charger.

PP pin is the proximity pilot or plug presence signal. The proximity pilot allows the light electric vehicle to detect when it is plugged in. PE pin is the standard protective earth.

The charging process is controlled through the control pilot pin(CP). The system is initially in AC mode. Therefore, when the plug is connected, the control of the charging process starts in accordance with the SAE 1772 standard for AC charging. This means control via a pulse-width modulation signal from the charging station side is used for AC mode. Different duty cycle reports different drawable currents from electric vehicle supply equipment. Table 2 shows the meaning of different duty cycles(D). If the duty cycle is equal to 5 % it is an indicator of the transition to DC mode. From the side of the electric vehicle, the current state of the charging process is reported using a change in voltage. All states are shown in table 3.

Table 2. A current corresponding to different duty cycles

Duty cycle	Maximum current
$D < 3\%$	0 A
$3\% \leq D \leq 7\%$	DC mode
$7\% \leq D \leq 8\%$	0 A
$8\% \leq D \leq 10\%$	6 A
$10\% \leq D \leq 85\%$	$D \cdot 0.6$ A
$85\% \leq D \leq 96\%$	$(D-64) \cdot 2.5$ A
$96\% \leq D \leq 97\%$	80 A
$97\% \leq D \leq 100\%$	0 A

Table 3. Determination of the state by the voltage

Voltage	**State**
+12 V	Not connected
+9 V	LEV is ready to charge
+6 V	LEV charge
+3 V	Ventilation is required
0 V	Error

After detecting a duty cycle of 5 %, it is required to switch the control pilot to CAN mode. Theoretically, it was possible to use CP and PP pins, switch them to CAN_H and CAN_L and use standard High-speed CAN, but this option requires two relays on the side of LEV. In addition, the proximity pilot adds safety to the process, since if the connector is torn out of the socket, the system will detect it immediately. Therefore, it was decided to use Single Wire CAN(SWCAN) technology. Single Wire CAN uses only one signal line as opposed to the usual CAN bus therefore for noise immunity it has a lower maximum possible transmission rate which equals 33.3 kb/s.

2.2.2. Communication protocol for DC charging

The communication works on the same principles as CHAdeMO and GB/T. The LEV battery management system controls the charging process using CAN messages. Interaction occurs according to the master/slave model, the vehicle is a master node and the electric vehicle supply equipment is a slave. Therefore, LEV messages have a lower identifier than charging station messages since information about the condition of the electric vehicle and errors is more important. If no message is sent within a second unless otherwise specified, the connection is terminated.

2.2.2.1. Message structure

The length of all messages is fixed and equal to 8 bytes. From the side of the light electric vehicle, three messages are used with IDs equal to 100, 101 and 102. From the side of the charging station, two messages are used with IDs 108 and 109. The description will explain the basic parts of the messages, but at the desire of the vendor, the free bytes of the messages can be filled with parameters to display something useful or send to the server of the central management system.

Table 4 shows the structure of the message from the LEV with an ID equal to 100. This message is only used to initialize the parameters of the LEV at the beginning of the interaction which means that all these parameters will be constant during the process. The obligatory part of the message is information about the total battery capacity and the maximum battery voltage. This message should contain authentication data, but since they depend on the type of authentication, therefore, in this structure, these fields remain reserved for the vendor.

Table 4. Message 100

Byte	**Content**	**Default**
0	Reserved for vendor needs	0x00
1	Reserved for vendor needs	0x00
2	Reserved for vendor needs	0x00

3	Reserved for vendor needs	0x00
4	Reserved for vendor needs	0x00
5	Maximum battery voltage	Calculated
6	Total battery capacity	Calculated
7	Reserved for vendor needs	0x00

Table 5 shows the structure of the message from the LEV with an ID equal to 101. This message is used to send information about the maximum possible and estimated duration of the charging process and the presence of dynamic charging. Charging is dynamic when the central management system can change the available current within the charging process. The message is sent during the first exchange of information and the dynamic charging process.

Table 5. Message 101

Byte	Content	Default
0	Dynamic charging(zero bit only)	0x00
1	Maximum charging time by 10 s	Calculated
2	Maximum charging time by 1 min	Calculated
3	Estimated charging time	Calculated
4	Reserved for vendor needs	0x00
5	Reserved for vendor needs	0x00
6	Reserved for vendor needs	0x00
7	Reserved for vendor needs	0x00

Table 6 shows the structure of the message from the LEV with an ID equal to 102. This message is used throughout all interaction processes. First, it is used dynamically during the charging process to request the calculated current value and battery capacity at the moment. Also, it is used to send information about errors, the current status of the charging process and the target battery voltage.

Table 6. Message 102

Byte	Content	Default
0	Reserved for vendor needs	0x00
1	Reserved for vendor needs	0x00
2	Target battery voltage	Calculated

3	Charging current request			Calculated
4	Fault flag	*Bit*	*Meaning*	
		0	Battery overvoltage	0
		1	Battery undervoltage	0
		2	Battery current deviation error	0
		3	High battery temperature	0
		4	Battery voltage deviation error	0
5	Status flag	*Bit*	*Meaning*	
		0	Vehicle charging enable(0:disabled)	0
		1	Vehicle connector locked(0:unlocked)	0
		2	Charging system fault	0
		3	Status of vehicle contactors(0:closed)	1
		4	Stop request	0
6	Current battery capacity			Calculated
7	Reserved for vendor needs			0x00

Table 7 shows the structure of the message from the charging station with an ID equal to 108. This message is used to send initial parameters from the charging station and dynamically control the charging process. It informs about the insulation test, the presence of welding detection support for an electric vehicle, the possibility of dynamic charging and the maximum voltage of the station. Also, for dynamic control, information about the available current and voltage is used.

Table 7. Message 108

Byte	**Content**			**Default**
0	Protection	Bit	Meaning	
		0	Welding detection support	0

		1	Insulation test	0
1	Reserved for vendor needs			0x00
2	Available output voltage			Calculated
3	Available output current			Calculated
4	Threshold voltage			8C
5	Reserved for vendor needs			0x00
6	Dynamic charging	Bit	Meaning	
		0	Dynamic charging enable	0
		1	Permission to reset maximum charging time	0
7	Reserved for vendor needs			0x00

Table 8 shows the structure of the message from the charging station with an ID equal to 108. This message is used throughout the charging process to track errors, station status, and remaining charge time. The “Present output voltage” and “Present charging current” are sent so that light electric vehicles can detect discrepancies between what the station supplies and what comes to LEV.

Table 8. Message 109

Byte	**Content**			**Default**
0	Reserved for vendor needs			0x00
1	Reserved for vendor needs			0x00
2	Present output voltage			Calculated
3	Present charging current			Calculated
4	Reserved for vendor needs			0x00
5	Status/fault flag	Bit	Meaning	
		0	Charger status: standby:0 or charging:1	0
		1	Charger malfunction	0
		2	Charging connector lock	0
		3	Battery incompatibility	0

		4	Charging system malfunction	0
		5	Charging stop control	1
6	Remaining charging time by 10 s			Calculated
7	Remaining charging time by 1 min			Calculated

2.2.2.2. Normal operation

Figure 19 shows the messaging process between a light electric vehicle and electric vehicle supply equipment for initialization, preparation for charging and during the charging process. The flags in brackets indicate the values under which the process runs normally. All interaction starts with sending initialization messages.

The next step is preparing for the charging process. A message from a light electric vehicle indicates that it is ready to charge and the connector is locked. After that, the charging station starts testing the insulation and reports the result. In response, LEV sends the message that the contactor is closed and waits for 1 second while the station checks this.

The third stage is the actual charging process. LEV requests a certain value of current cyclically and reports the current battery capacity. In response to this request, the station changes the “Charger status” flag and sends it with the supplied current and voltage values.

If dynamic charging is enabled, the central management system can change the available current during charging. EVSE should send a message about available current. In response to this message, the LEV sends a current request in accordance with the newly available output current.

Also, during dynamic charging, electric vehicles can change the maximum charging time, but it must be less than the remaining time allocated by the charging station.

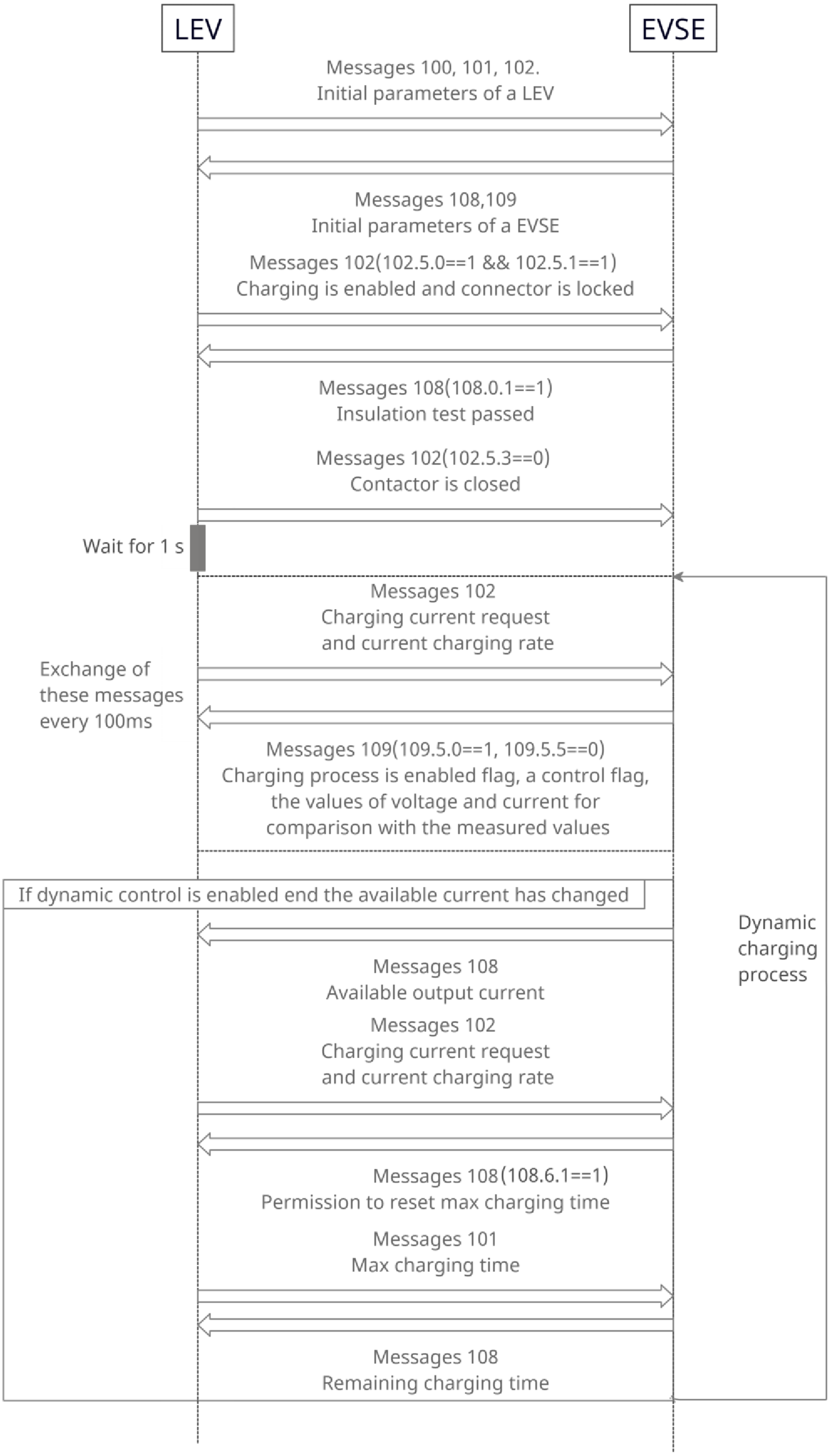


Figure 19. Normal initialization and charging process

The normal charging stop process can be initiated from both sides.

The normal charging stop on the LEV side occurs when the current battery capacity is equal to its maximum. On the EVSE side, a normal stop can be initiated when the user presses the stop button or if the charging time has reached a specified value. Figure 20 shows these two stop options. The difference is only in the order of the messages. From the vehicle side, a message to turn off charging and a request for zero current are mandatory and from the charging station side, a message to stop charging control is required.

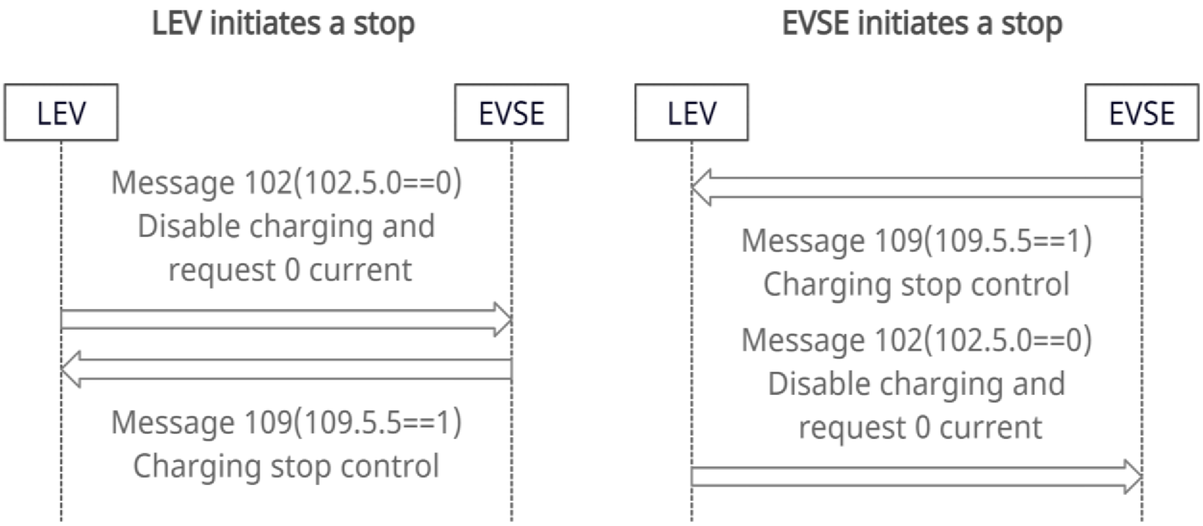


Figure 20. Normal stop initiation

After initiating a stop, it is required to complete the charging by safety requirements. This process is shown in figure 21. In the beginning, it is required to wait for the current to decrease to 5 amperes, after which EVSE sends reports that it is in standby mode. In the next step, the light electric vehicle informs about the successful opening of the contactor. Then the system waits for the voltage to drop to 10 volts and EVSE reports that the connector can be unlocked.

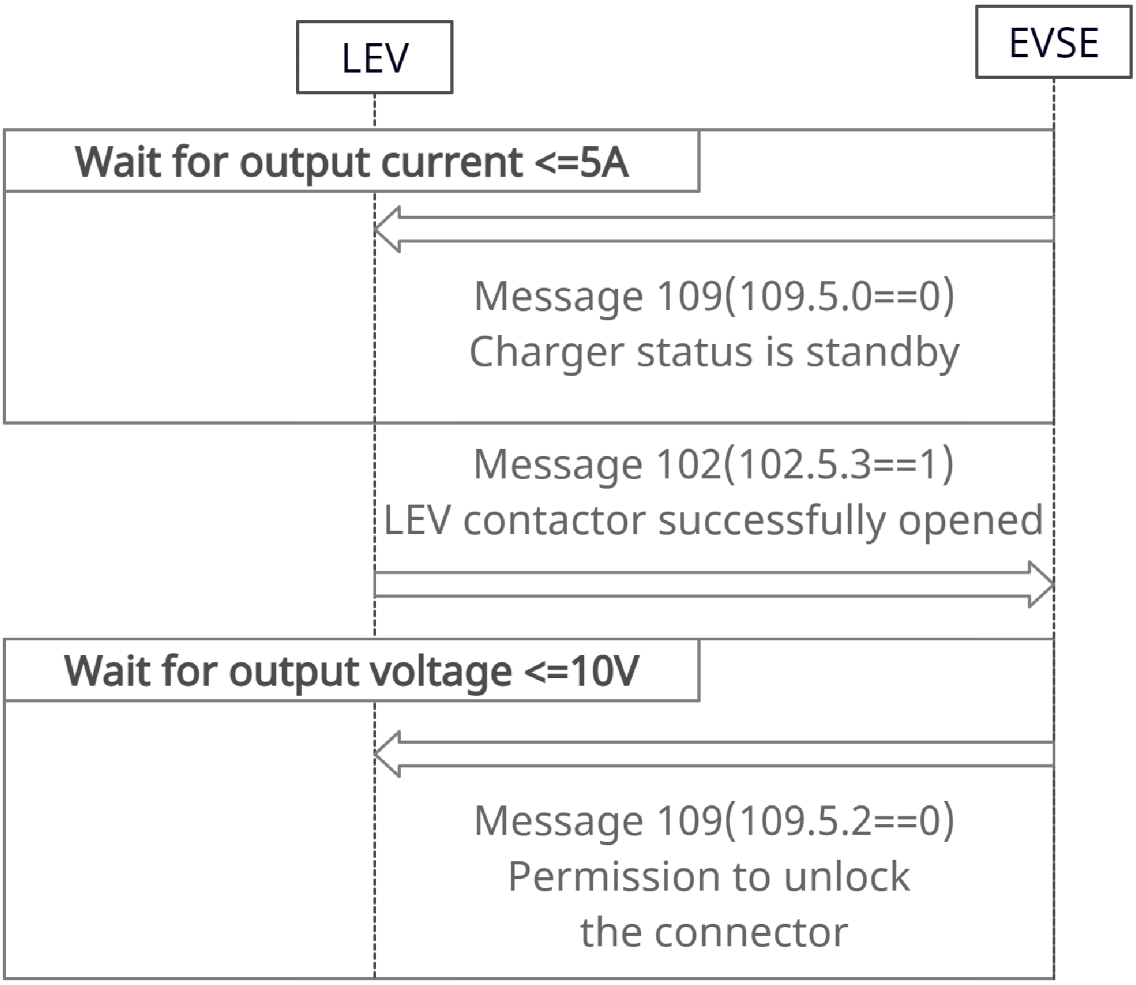


Figure 21. Safe stopping of the charging process

2.2.2.3. Abnormal cases

There are several variants of abnormal cases.

The first variant of the abnormal case is triggered when the transition to the next stage of the interaction is impossible due to incorrectly set status flags. This abnormal case could occur if the LEV battery is non-compliance with the capability of the charging station. For example, if the LEV requests a charging voltage beyond the maximum output voltage of the charger.

The second variant of the abnormal case occurs when the error flags change due to obvious failure in the system. For example, this type of error occurs when a station fails an isolation test. If any side of the interaction reports an error, the opponent should not report it again.

2.3. Control system with Human-Machine Interface for DC fast charging

The station control scheme is shown in figure 22. The principle of operation is based on switching between different states. Each state provides a specific set of actions. For each state, there are conditions for switching to another state, which are indicated by arrows in figure 22. For some states, the transition can be carried out unconditionally after the end of all actions of the state.

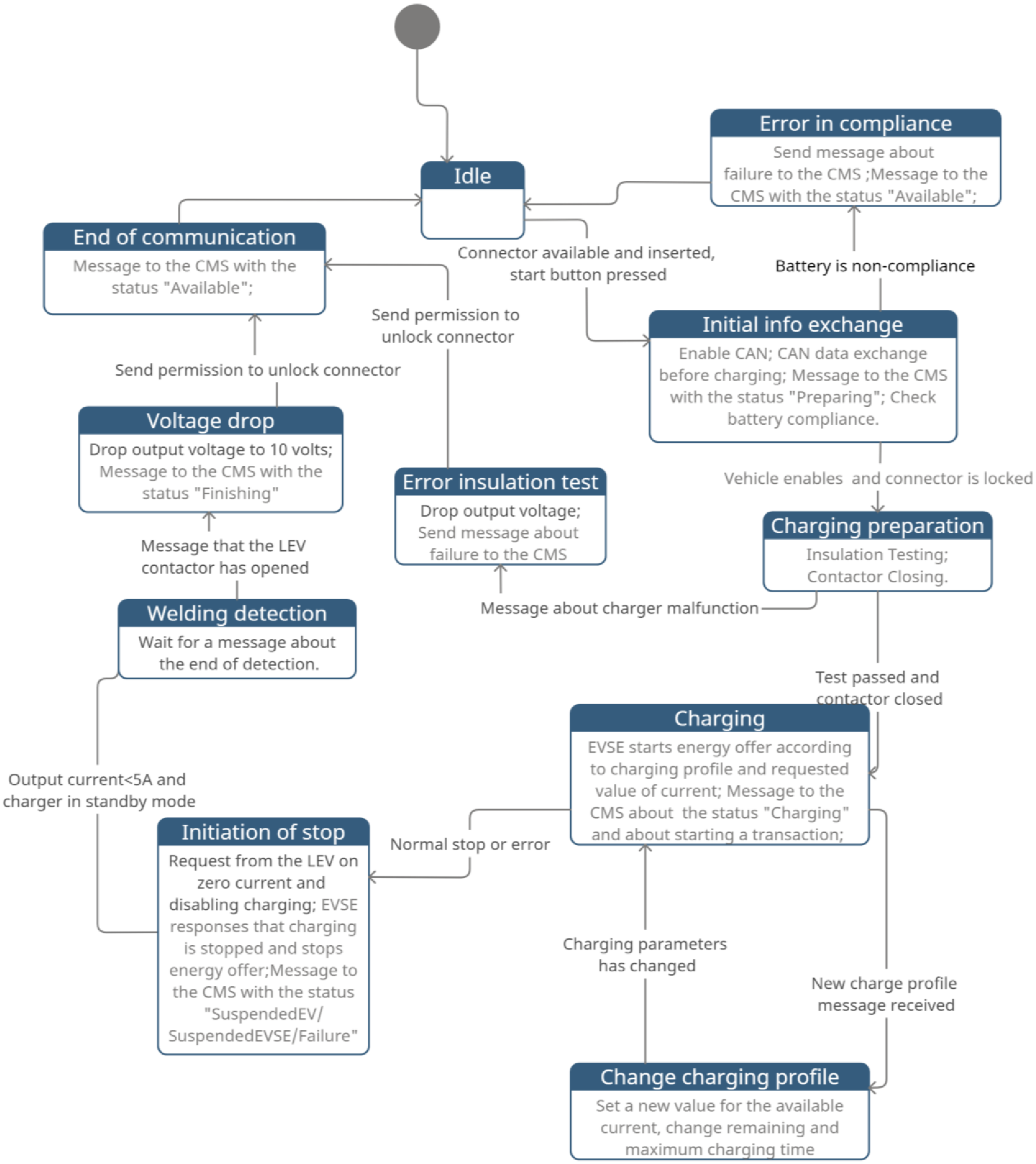


Figure 22. Scheme of control

The black circle indicates the process of turning on the charging station. The charging station goes into the “Idle” state after this. In this state, it waits for the LEV connection. When the user inserts the plug and presses the start button on the interface screen, the station enters the “Initial info exchange” state.

In the “Initial info exchange” state, the charging station provides a PWM signal of 5 % to switch on the single-wire CAN bus. Then the station receives the LEV parameters and transmits its parameters. The central system is informed that the station is now in charging preparation mode and is not available to other users. Some message parameters are calculated according to the data received during the exchange of information. The compatibility of the station and the LEV battery has to be checked. If they are not compatible, then the station goes into the "Error in compliance" state, informs the central system about the error and that the station is available to users again. The error state is shown in the user interface for a few seconds.

If the error is not detected, then LEV allows charging and informs about the connector lock, which is a signal to switch to the “Charging preparation” state. This stage is necessary to ensure safety. The charging station closes its contactors and performs insulation testing. In case of failure, it also goes into an error state, but different, since at this stage it is already required to stop the voltage supply and unlock the connector. The necessary actions for this will be described further.

If the test was successful and the vehicle reported that the LEV contactors are closed, then the station enters the “Charging” state. At this stage, the station begins to supply energy in accordance with the requested values. The EVSE also informs the LEV about the supplied values. This is required for process safety control. In addition, a start transaction request is sent to the central management system.

Charging profiles are used for remote control of the station. This profile contains the value of the current, which is available at the moment and may contain the new duration of charging. During the “charging” state the EVSE can get a message with a new profile from the central management system.

When a message about a new charging profile is received, the station switches to the "Change charging profile" state. In this state, the charging station reports a change in the available current and the LEV must request current according to the new value. In addition, the maximum and remaining charging time is recalculated according to the new values. After all the changes, the station returns to the "Charging" state again.

The remaining steps are used to safely stop the charging process. The charging stop can be initiated by LEV or EVSE.

Possible reasons for the request to stop from LEV:

- Battery is charged;

- Battery overvoltage;
- Battery undervoltage;
- Battery current deviation. This means that the measured current value does not correspond to the value from the station message;
- Battery overheating;
- Battery voltage deviation. This means that the measured voltage value does not correspond to the value from the station message;

Possible reasons for the request to stop from the charging station:

- The user pressed the stop button of the interface;
- High temperature;
- Long absence of a request for a current from LEV;
- Overvoltage was measured by the station;
- Overcurrent was measured by the station;
- Undervoltage was measured by the station;

Depending on the reason for the stop, different messages are sent to the central system. If the initiator is LEV, this is a “SuspendedEV” status message. If the initiator is EVSE, then the status message is “SuspendedEVSE”. If the reason for the stop is an error, a “Failure” status message is sent with a description of the error. The rest of the steps are the same for all cases. Both participants report a desire to stop the process and the charging station stops the energy offer, which means reduces the output current.

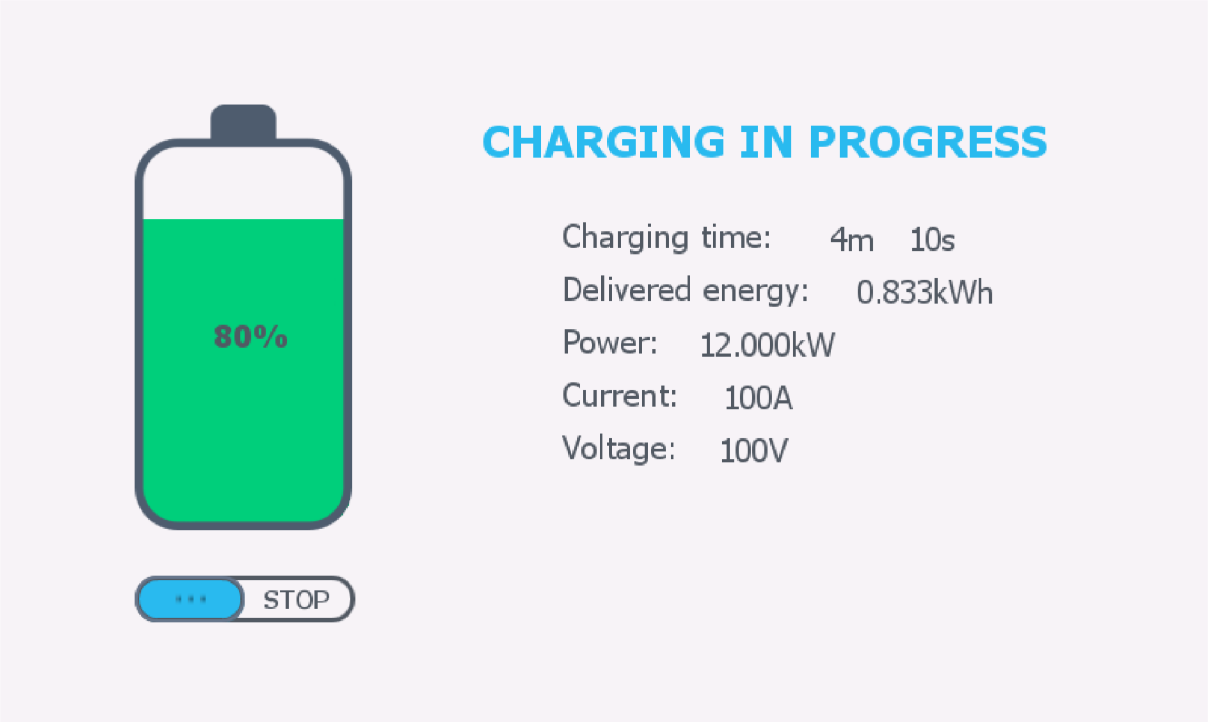
When the current falls below 5 amperes, the system must ensure that the welding detection process is completed. This process is labelled as the “Welding detection” state. The detection itself is performed on the LEV side. The transition from this state is carried out when a message about the contactor opening is received.

The next state is "Voltage drop". At this stage, the station reduces the voltage and informs the central system about the finishing of the charging process. When the voltage becomes less than 10 volts, the EVSE opens its contactors and sends a message about the possibility of disconnection. After that, the plug can be disconnected, and the station informs the central system that it is available again.

In this explanation, only the basic part of the interaction with the central system is presented. The organization of remote monitoring and control will be described in more detail in the corresponding chapter.

2.3.1. Human-Machine Interface

Figure 23 shows the Human-Machine Interface designed for the charging station. The battery indicator on the left of the screen shows the current battery percentage of the light electric vehicle. At the bottom of this indicator is a button to start or stop the charging process. The top right shows the current status of the charging station. It may be in three states: “Ready for charging”, “Charging in progress” and “Error occurred”. The remaining space contains technical parameters that show current information about charging time, charged capacity, output power, current and voltage.



CHARGING IN PROGRESS

Charging time: 4m 10s
Delivered energy: 0.833kWh
Power: 12.000kW
Current: 100A
Voltage: 100V

Figure 23. HMI of the charging station

2.3.2. Safety

The system report errors by changing the status on the screen, as well as sending a message to the central system.

At the stage of preparation for charging, the system starts the isolation monitoring device and supplies the test voltage. If the isolation monitoring device has not reported problems, then it is possible to continue working as usual, but if the problem is observed the station must shut down urgently. The monitoring device works during the entire time when the voltage is applied. The device is configured according to the permitted voltage range, so if it measures the voltage above or below this range, the charging process is also interrupted immediately, but in accordance with the specified stages of the safe end just like in normal operation.

After the contactors are closed and opened, the station checks the status of the corresponding auxiliary contactors before proceeding to further actions

2.4. Remote monitoring and controlling of DC fast charging

Since open networked systems are recognized as more convenient in many aspects, it was decided to make the station adapted specifically for this type of system. The Open Charge Point Protocol is currently the de facto standard for open networked systems for EV charging in the world [26].

Open Charge Point Protocol (OCPP) is an open communication protocol that defines the format for the exchange of messages between the charging station and the charging station management system (central system). This protocol is designed to control and monitor any type of charging system and is used by many manufacturers around the world.

At the moment, manufacturers use mainly three versions of OCPP. OCPP 1.5 is a too old version, which doesn't provide the smart charging function. OCPP 1.6 is the most popular version of OCPP among vendors of the charging station management system and it supplies the smart charging function. OCPP 2.0 is the latest version, which is not popular among vendors [27]. Since OCPP 1.6 is popular enough and has a smart charging function, version 1.6 is used in this project.

All main features of OCPP can be divided into six profiles:

1) Core – basic functionality of charging station;
2) Firmware Management – firmware update management and download of diagnostic log;
3) Local Auth List Management – management of the local authorization list in charging stations. The central system can send an authorization list from to charging station so it can perform authorization without needing the request to the central system;
4) Reservation – Features for reservation of charging stations by users;
5) Smart Charging - Load balancing and use of charge profiles. Smart charging provides control of power and current using limits for maximum power for every connected Electric Vehicle. It helps in enhancing grid stability. Scheduling the charging based on the Time Of Day tariff allows vendors to determine the workload of the station during the day and set the appropriate prices;
6) Remote Trigger - Features for remote triggering of charging station initiated messages.

To implement a profile, it is necessary to create a mechanism for creating and interpreting all of its requests and responses, and it is also necessary to organize the appropriate storage of the required data. Only the implementation of the Core is mandatory, other profiles are optional.

There are two different types of OCPP:

1) OCPP based on JSON-over-Websocket(OCPP-J)
2) OCPP based on SOAP(OCPP-S)

In accordance with the JSON-over-Websocket approach, the WebSocket protocol is used for data transfer over a TCP connection. The central system is the WebSocket server and the EVSE is the WebSocket client. Each station needs its WebSocket URL through which it can access the Central System's WebSocket server.

The WebSocket protocol itself has no way to distinguish between requests and responses. To encode these request/response relations, OCPP uses its own framework. The actual OCPP message puts into a wrapper that at least contains the type of message, a unique message ID and the payload, the OCPP message itself. The payload must be in the format of a JSON string.

Security in OCPP-J can be provided at the network layer or using OCPP-J over TLS. The first method could be used only if network is private and secure, but if network is not public, then the second method must be used. According to OCPP requirements, the TLS certificate shall be an RSA certificate with a size no greater than 2048 bytes.

In accordance with the SOAP approach, the HTTP protocol is used for data transfer over a TCP connection. The SOAP protocol defines the message structure in XML format. In this option, it is required to implement data compression, since the XML message can be quite large due to format features.

The transport of SOAP messages should be secured with SSL/TLS. Therefore, it is required to use HTTPS.

In the OCPP-J version, the WebSocket protocol allows data transfer in both directions, and both server and client can send messages simultaneously over a single TCP socket connection. In the OCPP-S version, it is necessary to use two distinct HTTP calls for both the client and the server requests. This means that in OCPP-J only the charging station initiates the connection and then both participants can send requests, and in OCPP-S the central system must also initiate the connection in order to be able to send requests. Therefore, in OCPP-S, each charging station must have a public IP address for connection to it. In this aspect, OCPP-J is more convenient than OCPP-S.

In terms of the sending data format, using JSON format is easier and more convenient than XML in the case of parsing. Also, XML format is very bulky, unlike JSON, and it can require the use of compression algorithms.

In terms of relevance, most vendors of the Charging Station Management Systems usually prefer the OCPP-J version of the protocol. This is an important factor because it provides a more complete realization of the open protocol advantages, so it gives a large choice between suppliers of central systems.

Among other things, using the SOAP approach makes it impossible to easily switch to new versions of OCPP, since they no longer support the outdated SOAP approach.

As a result of comparing these approaches to the implementation of the OCPP protocol, it is concluded that the approach using JSON over the Websocket protocol is much better and is therefore used in this project.

2.4.1. Implementation of the OCPP client

The implementation of the WebSocket and TLS protocols and parsing of the JSON format are unnecessarily complex tasks for the PLC. Siemens has not yet provided tools to implement such a protocol. For this reason, a separate device is required to interact with the OCPP server.

A sufficiently convenient solution is to use some device with Linux OS, for example, Raspberry Pi, for which ready-made OCPP libraries are written. Therefore, for such devices, it is only necessary to design interaction with a PLC.

The Siemens S7-1500 controller has an integrated OPC UA server, that enables the Linux PC program to get the current value of PLC variables and change them [28]. OPC UA is platform-independent standard that enables the secure exchange of information in industrial systems. Security is provided by authentication and authorization, encryption and data integrity assurance using signatures. OPC UA can be implemented using .NET, Java or C. The highest performance is provided by the .NET approach. OPC UA is based on client-server interaction. The Linux PC client can request data from the server and change it in real time. The client and server connect via Ethernet and exchange data over TCP/IP.

This approach is convenient and has many advantages. The advantages depend on the environment in which the station is used.

If this is a stand-alone station, then the advantage is that in case of disconnection with the OCPP server, the station can continue to work offline using local lists for authentication, storing transactions in memory and when the connection with the server returns, transmit this data to the central system.

On the other hand, it is possible to use the topology shown in Figure 24.

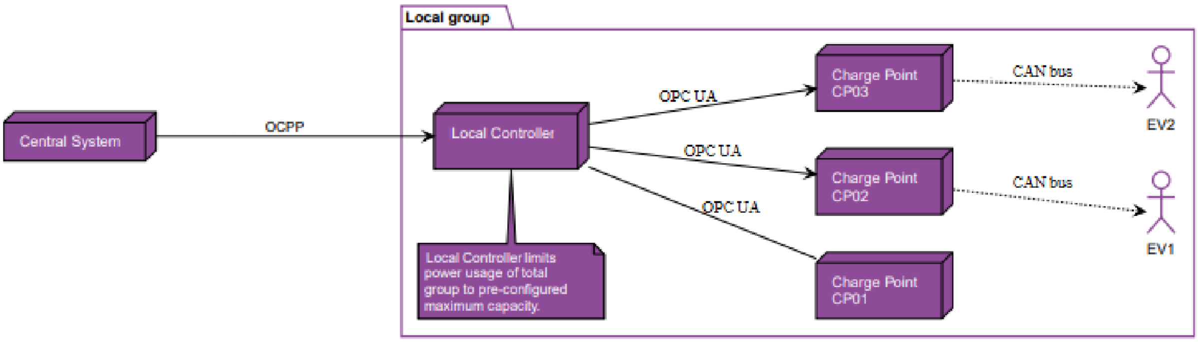


Figure 24. Multiple charging stations connected to central system via local controller

Linux PC is a local controller in such a system to which a local group of stations is connected. Like a stand-alone station, when the connection with OCPP is disconnected, the local controller can store transaction data and use the local list for authentication and, accordingly, ensure normal operation. But in addition, local load balancing algorithms can be implemented in the local controller to ensure maximum performance despite the loss of communication with the central management system.

In this paper, a more universal version of the charging station is considered, therefore, only the algorithm of operation for one station connected to a Linux PC is designed.

2.4.2. The algorithm of OCPP operation

As described above, OCPP has six main profiles: Core, Firmware Management, Local Authorization List Management, Reservation, Smart Charging and Remote Trigger. The Remote Trigger, Reservation and Firmware Management profiles are not considered in this work, as they make sense only for vendor-specific tasks. The Local Authorization List Management profile works on the Linux device side as usual for OCPP and does not require special interaction with the PLC charging process manager. There is no difference between a local and a regular list for EVSE. Therefore, the algorithm of operation for Core and Smart Charging profiles will be considered.

On the Linux device side, OCPP works in accordance with the standard algorithm of operation, but it is required to determine the algorithm of interaction between Linux PC and PLC. This requires to provide access to the certain PLC data. Such data are the initial configuration of the station, the dynamic state of the station and the state of the light electric vehicle and some controlling flags.

The initial configuration of the station is the station parameters such as the maximum possible voltage, the maximum possible current, the possibility of dynamic charging, availability etc. Thus, these are the parameters of the station that do not change at all or can only be changed in the “Idle” state. The states of these variables are changed using “ChangeConfiguration” requests. Also, the availability parameter should be changed by the “ChangeAvailability” request. All these notifications relate to the Core profile.

On the other hand, the dynamic state of the station is the parameters of the station that can change during charging. These are parameters such as the available output current and voltage, the maximum allowed charging time etc. These parameters are changed using the Smart Charging profile. These parameters can be changed during the charging process using the “SetChargingProfile” request. Also, in the standby state of the station, these default parameters can be set by the same request, but with the corresponding parameters.

The state of a light electric vehicle is the parameters received from the transport, such as the maximum voltage, maximum and estimated charging time, authentication information, error flags, etc. These parameters are used for monitoring using “Status Notification”.

In general, “Status Notification” is used to transmit the information necessary for remote monitoring. When the charging station changes the state to another, it is required to send a “Status Notification” with the corresponding status, therefore access to status variables is required. Also this notification sends error information which are tracked using the corresponding PLC flags.

To be able to remotely start and stop the charging process, “RemoteStartTransaction” and “RemoteStopTransaction” requests are used, their execution occurs by changing the “Start” button variable.

The start and end of the power supply process is reported using the “StartTransaction” and “StopTransaction” requests to the Central System. The charging station cannot start the charging process and allow the user to pull out the connector without the permission of the central system. Therefore, it is required to set the appropriate PLC flags to inform about the permissions.

Conclusion

The purpose of this work was to develop a project of a DC fast charging station suitable for light electric vehicles. To do this, during the development process it was necessary to take into account the design differences between light electric vehicles and usual electric vehicles. Therefore, the variability of the forms of such transport, their small size and the small required voltage were considered.

The existing standards in the field of DC fast charging stations for usual electric vehicles were investigated for this development. It was determined that the existing connector standards are not suitable for light electric vehicles, therefore modified or new non-standard versions are required. As a result of the study, it was concluded that networked charging stations with open protocols of operation are the most profitable solution, which gives abundant opportunities for vendors of charging stations.

The next step was to select and design the hardware of the charging station. The device is designed in accordance with the safety standard of the charging process described in IEC 61851-23 [21]. During the design process, two non-standard connectors were considered, since the structure of the station depended on the type of connector. The first type is a completely new connector with CAN bus control, and the second is a modified version of the AC type 2 connector, which was proposed by Ing. Ondřej Mach. As a result of comparing the advantages and disadvantages, the second variant of the connector was chosen and the station was designed specifically for it.

At the next stage of work, a proprietary protocol of interaction between the station and a light electric vehicle was developed for the selected connector. During the development, the possibility of combined operation of the connector was provided.

The next stage of the work was the control system organization of the whole charging station. Control is organized through the change of states. Certain parts of the system only work in a certain state. A human-machine interface is developed for the system because users need to control the charging process.

The last step was to provide the possibility of remote monitoring and control of the station. For this purpose, a convenient OCPP protocol was chosen. It was determined that it is currently impossible to implement OCPP on a PLC. Therefore remote monitoring and control are carried out using a separate device with Linux OS, which is an OCPP client connected to the central management system. This Linux device communicates with PLC via OPC UA. Since the implementation of OCPP is not a problem for a Linux device, the paper describes only the algorithm of interaction between the Linux device and the PLC in order to provide the required reading and modification of PLC data.

As a result, the initially set goals were achieved and the DC fast charging station for light electric vehicles with the possibility of remote control and monitoring was successfully designed.

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